VERTICAL FLOW SYSTEMS – EFFECTS OF TIME AND ACIDITY RELATIONS[1]

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Abstract. The characteristics of the 29 vertical flow systems reported on by Rose and Dietz (2002) have been reevaluated based on 2 years additional experience and revised understanding of acidity. Data on several additional systems have been collected. If measured hot acidity is interpreted as net acidity that includes the effects of alkalinity (vs. net acidity = acidity minus alkalinity), many systems remove slightly less acidity and fewer VFS produce net alkaline water. Rates of acidity removal ($g/m^2/d$) are somewhat lower, and the typical value is about 34 rather than 40 $g/m^2/d$. If non-Mn acidity is taken as the critical parameter, the sizing parameter for non-acid effluent is about 35 $g/m^2/d$. Systems with fine limestone in the compost do about twice as well and appear to be a solution for high-Al discharges.

Over the past 2 years, at least 5 of the systems have markedly decreased in effectiveness. Problems have been accumulation of excess ferric hydroxide precipitate on top of the compost, pipe plugging, channeling, and Al coating causing decreased reaction rate with limestone.

Additional key words: Passive treatment, SAPS, performance, problems.

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Introduction

Vertical flow systems (VFS), typically consisting of a compost layer overlying a bed of limestone, also called vertical flow ponds (VFP), SAPS, and RAPS, have become a major method of passively treating net-acid mine drainage. To treat a given acid mine drainage (AMD) discharge, the VFS must be properly sized, designed and constructed. In order for these systems to be economical, they must treat the AMD for a life of 20 years or so with minimal maintenance expense (Rose, 2003). Some systems have failed or declined in effectiveness (Ziemkiewicz et al., 2002), so an evaluation of reasons for success vs. failure is desirable. Rose and Dietz (2002) compiled data on 29 VFS and presented data showing that an areal acidity loading of about 40 g/m^2/day was typical of successful units, and that addition of limestone to the compost was beneficial. A conservative design guideline of 25 $g/m^2/d$ was suggested.

Previous work used net acidity as a measure of treatment effectiveness, and calculated net acidity as:

$$\text{Net Acidity} = \text{Measured Acidity} - \text{Measured Alkalinity} = (-)\text{Net Alkalinity} \qquad (1)$$

It is now evident that acidity measured by Standard Methods (1995, 1998) or EPA method 305 is actually net acidity, because alkalinity is effectively titrated and subtracted from the acidity titration (Cravotta and Kirby, this volume). Specifically, according to Standard Methods (1995, 1998), if the sample contains hydrolyzable bases or reduced cations (i.e., Fe^{3+}, Fe^{2+}, Al^{3+} Mn^{2+}), the first step is to titrate to pH <4.0 with standardized H_2SO_4. An aliquot of H_2O_2 is then added and the sample is heated to boiling, cooled, and then titrated with standardized NaOH to pH 8.3. The acidification converts all HCO_3^- to dissolved CO_2, which is then driven off on heating so as to avoid counting dissolved CO_2 as acidity. The titration with base measures the contribution of Fe, Al, Mn and H^+ to acidity. The acidity is then calculated as

$$\text{Acidity (mg/L } CaCO_3) = 50{,}000\,(A \times B - C \times D)/S \qquad (2)$$

where A and C are ml of standard NaOH and H_2SO_4, respectively, B and D are the normality of the base and acid, respectively, and S is the sample volume in milliliters. Subtraction of C x D amounts to subtraction of alkalinity from acidity, to give net acidity. If the value is negative, the value is to be reported as a negative number. The use of equation (1) is therefore incorrect if the Standard Methods acidity procedure is used. Acidity values of zero, commonly reported in the past when acidities are negative, are not useful as net acidities.

In view of the fact that most acidities measured on AMD in Pennsylvania are measured by the Standard Methods procedure, a major purpose of the present paper is to reevaluate the results of Rose and Dietz (2002) with this revised understanding. Note that the definition that Net Acidity = (-) Net Alkalinity is still used in the following. Also, in the remainder of the paper, acidity means net acidity unless stated otherwise.

At least 2 years more information has been accumulated on the performance of many of the systems discussed in Rose and Dietz (2002), and data has been obtained on several additional systems. The acidity removal rates on these systems are added to the database, and the effectiveness and failure information on the systems are updated. Reasons for declines in effectiveness are discussed, as well as improved design features.

Compilation of Information

Table 1 lists basic information on the 15 additional systems. For some systems, data are incomplete or limited, but the expansion of the database is considered to make inclusion worthwhile. Most data were compiled from sampling by other workers. The values are generally total metals and acidity by Standard Methods procedures, in view of the fact that these methods are acceptable to PA DEP. Sampling at the Pot Ridge, Glasgow and Power sites was by the writer, with metal analyses at the Penn State Materials Characterization Lab and acidity by Standard Methods (1998).

Table 2 lists chemical data on the additional systems, and Table 3 lists revised data on the previously reported systems. Net acidity has been calculated by the following procedure:

1. If a non-zero measured acidity value is available, then this value is used as a net acidity.
2. If the measured acidity is reported as zero (as has commonly been reported when acidity is actually negative), then net acidity is calculated as

$$\text{Net Acidity (mg/L CaCO}_3\text{)} = 50(2C_{Fe}/55.85 + 2C_{Mn}/55 + 3C_{Al}/27 + 10^{3-pH}) - \text{Alk} \qquad (3)$$

where C is concentration in mg/L and Alk is measured alkalinity.

Table 1. Basic data for systems in addition to those in Rose and Dietz (2002)

Name	Built Year	Flow L/min	Flushable	Water depth m	Compost th. m	Ls. Thickn. m	Area m2	Ls size cm	Acid. In mg/L	Acid. Out mg/L
Coldstream A	98	205	Y	1.5	0.6	0.9	2400		582	-235
Coldstream B	98	50	Y		0.6	0.9	650		685	-154
Tangascootack 1	98	155	Y	1.5	0.3	0.6	960	2.5	235	75
Tangascootack 2	99	130	?				984		43	-125
Tangascootack 3	00	60	Y				542		74	-116
Glenwhite SqF	99	200	Y				440		194	48
Glenwhite SpH	01	400	Y				2545		106	-200
Glasgow 1	99	120	Y				2800		1230	778
Glasgow 2	99	120	?				1900		685	382
Power	99?	380	N				4850	10	400	26
DeSale I	00	102	Y				1340	2.5	439	133
DeSale II R	00	172	Y	0.9	0.15	1.35	1600	10	269	-63
DeSale II L	00	105	Y	0.9	0.15	1.35	1600	10	269	-100
PotRidge A1	97	57	N				1070		1046	702
Pot Ridge A2	97	57	N				1070		702	367

Table 2. Chemical data for additional systems

Name	Period	N	Acidity in mg/L	Non-Mn acidity in mg/L	Acid load g/m2/d	Non-Mn acidity load g/m2/d	Acidity out mg/L	Non-Mn acidity out mg/L	pH in	Fe in mg/L	Al in mg/L	Mn in mg/L	Mn out mg/L	Al areal flux g/m2/d	Acidity removed mg/L	Acid. Removal rate g/m2/d
Coldstream A	4/99-5/02	23	582	579	72	71	-235	-237	2.5	105	48	2	1.1	5.90	817	100.5
Coldstream B	4/99-5/02	20	685	683	137	136	-154	-155	2.5	115	35	1	0.5	6.98	839	167.3
Tangascootack 1	7/98-12/99	18	235	113	55	26	75	-31	3.4	4	24	67	58	5.58	160	37.2
Tangascootack 2	8/99-11/02	18	43	12	8	2	-125	-143	4.3	2	0.3	17	9.8	0.06	168	32.0
Tangascootack 3	3/02-10/03	10	74	63	12	10	-116	-121	4.2	1	3.3	6	3	0.53	190	30.8
Glenwhite SqF	2/01-2/02	26	198	187	124	117	78	68	4.0	97	1	6	5.5	0.62	120	75.0
Glenwhite SpH	4/01-2/02	10	106	101	24	23	-200	-204	3.4	1	7	3	2	1.58	306	69.3
Glasgow 1	6/01-11/03	2	1234	963	76	59	778	505	3.6	281		149	150		456	28.1
Glasgow 2	10/03	1	685	685	62	62	382	382	2.8						303	27.6
Power	10/03	1	403	403	45	45	26	26	2.9						377	42.5
DeSale I	9/00-10/02	1	439	297	48	33	133	11	4.0	139	8	78	67	0.88	306	33.5
DeSale II R	1/01-8/02	15	269	153	42	24	-13	-80	3.2	27	11	64	37	1.70	282	43.7
DeSale II L	1/01-8/02	15	269	153	25	14	-54	-136	3.2	27	11	64	45	1.04	323	30.5
Pot Ridge A1	12/97-8/00	6	1046	939	80	72	702	595	3.0	231	70	59	59	5.37	344	26.4
Pot Ridge A2	12/97-8/00	6	702	595	54	46	367	260	3.6	149	45	59	59	3.45	335	25.7

Table 3. Revised data for sites of Rose and Dietz (2002)

Name	Built	Flushable	Period	N	Acidity in	Non-Mn acidity	Acid load	Non-Mn acidity load	Al in	Al areal flux	Acidity out	Non-Mn acidity out	Acidity removed	Area	Flow
					mg/L	mg/L	g/m2/d	g/m2/d	mg/L	g/m2/d	mg/L	mg/L	mg/L	m2	L/min
Filson 1	94	N	12/96-11/97	11	241	154	96	61	14	5.57	175	82	66	420	116
Howe Bridge	91	N	1/92-9/00	41	323	254	60	47	0	0.00	106	40	217	1125	144
Pot Ridge Test	95	N	11/95-11/00	28	396	354	33	29	19	1.56	34	-2	362	1330	76
Pot Ridge C6	97	N	7/97-11/00	14	399	355	111	99	16	4.46	223	181	176	1110	215
Pot Ridge C10	97	N	12/97-11/00	12	201	157	63	50	12	3.79	89	53	112	980	215
Oven Run D1	95	N	10/95-9/00	14	114	61	44	24	2	0.78	10	-41	104	1200	323
Oven Run D2	95	N	10/95-9/00	14	10	-41	4	-17	1	0.42	5	-39	5	1160	335
Oven Run E1	97	Y	7/98-9/99	15	217	197	45	40	15	3.08	84	64	133	3510	500
Oven Run E2	97	Y	7/98-9/99	14	72	52	15	11	8	1.64	35	15	37	3510	500
Oven Run B1	99	Y	6/00-2/01	9	506	470	74	69	42	6.17	254	254	252	8008	817
Oven Run B2	99	Y	6/00-2/01	9	242	207	37	31	28	4.24	-47	-85	289	7774	817
McKinley	96		12/96-11/97	10	101	35	14	5	2	0.27	4	-27	97	600	57
Hortert	99		2/99-3/01	26	106	2	10	0	3	0.28	15	-43	91	480	31
Harb.-Walk	99	Y	12/99-5/01	13	205	170	30	25			4	-27	201	410	42
BEL1	96			11	105	101	73	70			52	48	53	395	190
BEL2	96			11	52	48	28	26			5	1	47	498	185
LLC2	95			16	183	92	89	45			131	42	52	295	100
LLC3	95			16	131	42	53	17			120	36	11	357	100
LLC4	95			16	120	36	88	27			50	-28	70	197	100
PMAC	96		6/97-3/99	48	196	178	5	5			3	-15	193	223	4
USC2	96			19	44	9	11	2			-24	-53	68	395	70
Rock Run 1	99		8/00-3/01	10	129	121	57	53	11	4.84	78	70	51	324	99
Rock Run 2	99		8/00-3/01	10	12	8	8	5	0	0.00	14	12	-2	245	112
Lambert	97?	Y	2/00-5/01	14	66	41	10	6	8	1.24	-99.4	-112	165	335	36
USC1	96		2/97-6/99	19	256	192	38	28			196	196	60	662	68
Sommerville	95		11/96-10/97	12	390	324	40	33	48	4.86	239	239	151	1350	95
Maust 1	97		10/97-6/01	15	154	127	32	26	3	0.62	-166	-166	320	1225	177
Maust 2	97		10/97-6/01	14	-168	-186	-54	-60	0	0.00	-220	-220	52	792	177
Jennings	97	N	?	8	272	239	26	23	23	2.22	-165	-165	437	1000	67

Plots of measured acidity vs. acidity calculated by eq. (3) for a group of systems indicate that this relation is reasonably accurate except for waters with obvious large amounts of suspended Fe hydroxides, such as those in the water discharging from an ALD as at Howe Bridge. The rationale for using a factor of 2 for Fe is explained by Cravotta and Kirby (this volume). Hedin (this volume) also shows that this relation is reasonably accurate. For computation of non-Mn acidity, the Mn term in eq. 3 is set to zero, or the Mn contribution in eq. 3 is subtracted from net acidity.

For the 29 systems previously reported in Rose and Dietz (2002), the average Fe, Mn, Al and pH values reported in Table 2 of that paper have been used in equation (3). The areal acidity loading is calculated as

$$\text{Areal Acidity Loading (g/m}^2\text{/d)} = A_{in}Q/S \qquad (4)$$

where Q is the flow rate, S is the water surface area of the VFP and A_{in} is influent net acidity. The water surface area is used rather than the compost or limestone area because satisfactory values for the latter dimensions were not available for many sites, and attempts to estimate them led to aberrant values. Similarly, the areal acidity removal rate is calculated as:

$$\text{Areal Acidity Removal Rate (g/m}^2\text{/d)} = (A_{in}-A_{out})Q/S \qquad (5)$$

Many of the systems have been revisited in the field and re-sampled during late 2003, and sources of information have been solicited for recent data in 2003. Recent acidity removal rates have been compared with earlier ones to indicate the performance of systems. Note that comparisons may be affected by the fact that 2003 was much wetter than the previous few years.

Areal Loading Results

Fig. 1 shows the revised acidity relationships on a plot of effluent net alkalinity vs. acidity loading in g/m^2/d. The sites are divided into four groups: “Normal” sites, “Degraded” sites, “Enhanced” sites and “Second Units”. The “Degraded” sites are known to have some problem (channeling through the compost layer, extreme Al or Fe, significant plugging) (Rose and Dietz, 2002). The “Enhanced” sites have limestone added to the compost layer (Maust 1 and 2, Jennings), or have influent pH much less than 3 (Coldstream). The “Second units” are VFS that treat the effluent from a preceding VFS, and have relatively low influent acidity (<75 mg/L). These units seem to generate little alkalinity, as does the Hortert site with low influent acidity. Other sites are “Normal”.

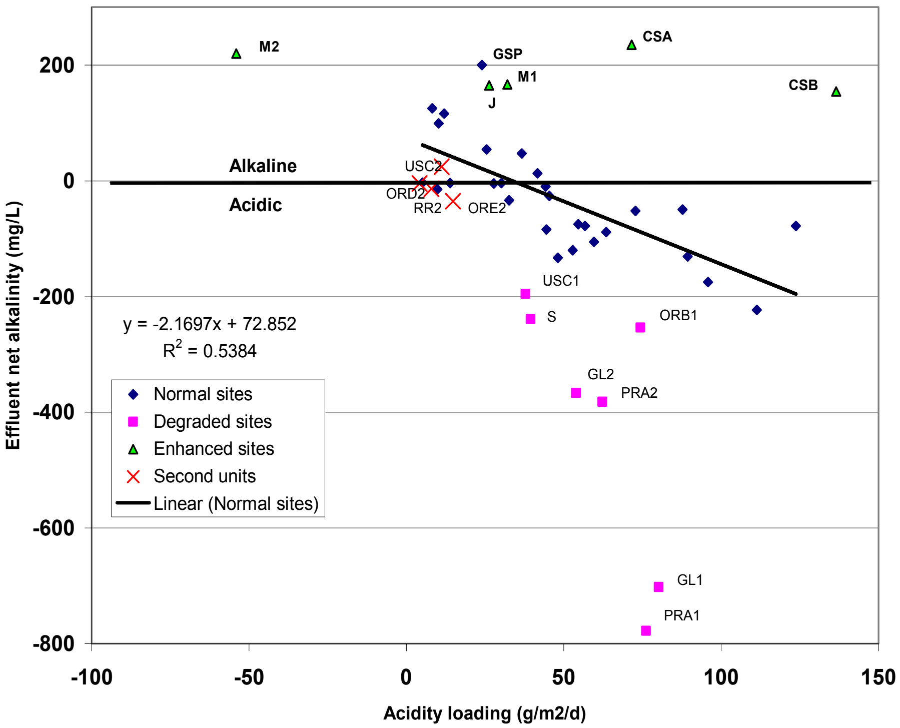

Figure 1. Effluent net alkalinity vs. areal acidity loading rate for VFS. The line is fitted to the “normal” sites. GL1, Gl2 = Glasgow 1 and 2, PRA1, PRA 2 = Pot Ridge A1, A2, M1, M2 = Maust 1 and 2, CSA, CSB = Coldstream A and B, J= Jennings, GSp = Glenwhite Sph, ORD2= Oven Run D2, ORE2 = Oven Run E2, RR2 = Rock Run 2 and USC2 = USC2.

The “Normal” sites show a trend similar to that found by Rose and Dietz (2001). Sites with low areal acidity loading (up to about 35 $g/m^2/d$) tend to have net alkaline effluents, and those with higher loading tend to have net acid effluents. The regression for these sites indicates that a loading of 34 $g/m^2/d$, on average, separates the net acid from net alkaline sites. Although the data show considerable scatter, the regression is significant at the 99% confidence level. This is lower than the 40 $g/m^2/d$ found in the previous evaluation but well above the value of 25 $g/m^2/d$ suggested as a design criterion (Rose and Dietz, 2002).

The three sites known to have fine limestone added to the compost (Maust 1, Maust 2, Jennings) all show effluent alkalinities distinctly higher than the trend. This design appears to be superior to systems lacking added limestone, as discussed below.

Several published experiments show a similar enhancement from addition of limestone to the compost. Thomas and Romanek (2002a,b) found very high treatment rates in limestone-buffered organic substrate in experiments with highly acid (acidity 1300 mg/L $CaCO_3$) runoff from a coal pile. Their compost contained a considerable fraction of wood chips. The effluent had net alkalinities averaging 1800 mg/L $CaCO_3$ at areal acidity loading rates averaging 58 $g/m^2/d$. The Fe and Al reacted with the fine limestone to precipitate in the compost as ferric hydroxides and Al hydroxysulfates. The precipitates were zoned down the reactors by pH and redox, with ferric precipitates formed first, then Al precipitates, and finally Fe sulfides. No plugging was observed during a two-year experiment. Gusek and Wildeman (2002) found excellent removal of Fe and Al for a limestone-amended compost in experiments with highly acid waters conducted for PA DEP. Brenner et al. (2003) described zoned Fe and Al behavior similar to the Thomas experiments in the limestone-amended compost at Jennings. Jennings is one of the sites showing enhanced removal, and has been operating for 6 years without plugging of the compost. In contrast, the Jennings ALD, treating the same water, plugged after 6 months (Watzlaf et al., 1994). The design of fine limestone mixed with compost appears capable of successfully removing Al as well as Fe at rates much higher than normal sites.

Some spent mushroom compost contains small amounts of limestone when received. However, the amounts are very small, because the limestone is added at rates of about 10 wt percent to only the top 5 cm or so of peat moss that caps the much thicker compost, according to staff at the Penn State Mushroom Research Lab. This small amount of limestone may be partly responsible for the initial high performance of some systems, but is inadequate for any long-term effect.

The Coldstream A and B sites also remove acidity at very high rates but do not have limestone added to the compost according to the designers (PA Bureau of Abandoned Mine Reclamation). A probable reason for the high effectiveness of these systems is the very low pH (2.5-2.7). The very low pH may prevent precipitation of Al until the water reaches very high P_{CO2}. This in turn promotes more limestone dissolution. The influent does contain 35-50 mg/L Al, and, as discussed later, the effectiveness of Coldstream A and B is declining, apparently due to Al coating of limestone after 5 years of operation.

The DeSale II sites also show an above average removal of acidity. No limestone was added to the compost at these sites (Slippery Rock Watershed Coalition, 2000). However, these sites do have a much more closely spaced underdrain system designed to promote uniform flow through the system. It seems possible that this has enhanced the performance of these systems. However, DeSale I, with a similar underdrain, lies below the regression line.

It is generally recognized that Mn is not removed in a VFS. Therefore, it seemed of interest to evaluate non-Mn acidity as a measure of system effectiveness. Jage et al. (2000) have previously found this parameter to be meaningful. The value is calculated as

$$\text{Non-Mn acidity (mg/L } CaCO_3\text{)} = \text{Net Acidity} - 1.81\ C_{Mn} \qquad (6)$$

where C_{Mn} is the manganese concentration in mg/L. The non-Mn acidity areal loading and the non-Mn acidity removal rates are calculated as in eq. (4) and (5) except that the acidity values are non-Mn net acidity rather than total acidity.

The plot of acidity loading vs. effluent alkalinity for non-Mn acidity is shown as Fig. 2. It is crudely similar to Figure 1, though the values tend to be more alkaline, as expected, and the intercept for net alkaline water is about 40 $g/m^2/d$. The fit is essentialy the same ($R^2 = 0.52$ vs 0.54 for simple net acidity). The results indicate that the Mn effect is not crucial to understanding the effectiveness of VFP's. In addition, one would probably like to produce effluent with sufficient alkalinity to neutralize Mn acidity, even if this does not occur in the system itself.

As shown by Rose and Dietz (2002), the acidity removed varies over a wide range, from about 50 to 360 mg/L for normal systems. Removal for the enhanced systems is up to 840 mg/L for the Coldstream systems. Note that even several of the "degraded" systems are removing more than 300 mg/L. These are systems with extremely acid inflow.

Long-Term Performance and Changes in Effectiveness with Time

For 15 sites, monitoring information is available for both a pre-2001 period (Rose and Dietz, 2002) and a more recent period. The data are summarized in Table 4. Performance is compared in Fig. 3 and 4.

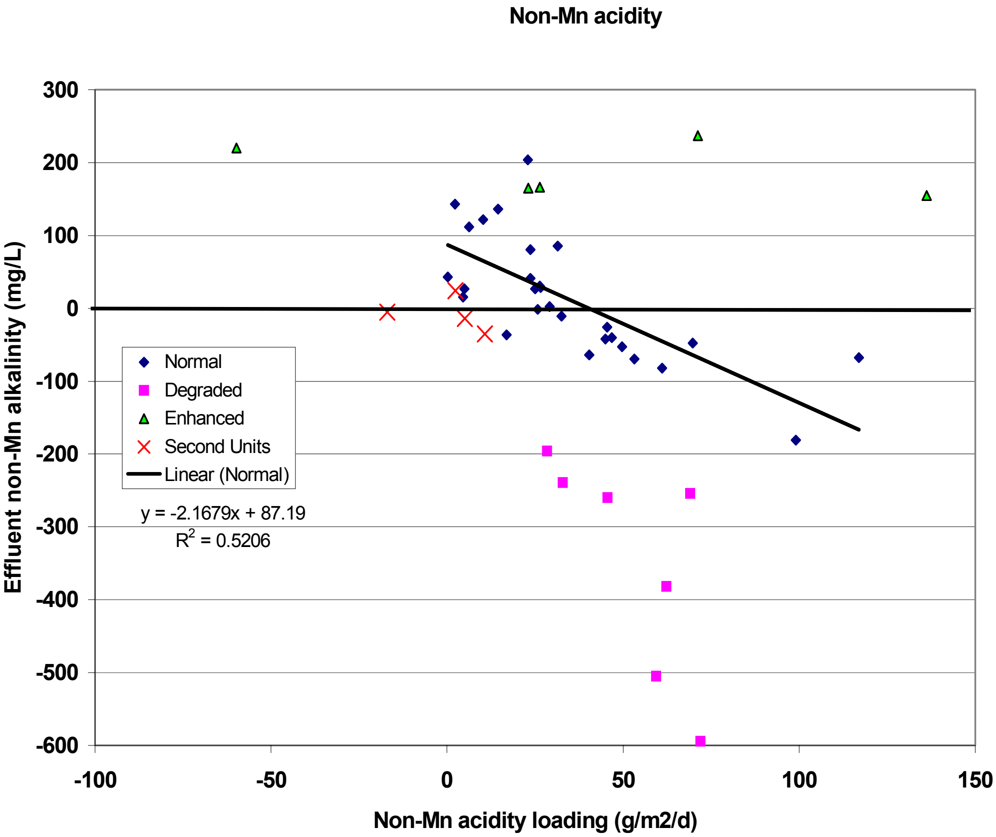

Figure 2. Effluent non-Mn alkalinity vs. Non-Mn areal acidity loading.

Table 4. Data for recent period.

Name	Period	N	Acidity in mg/L	Acidity out mg/L	Acidity removed mg/L	Flow L/min	Acidity removal rate g/m2/d
Pot Ridge Test	3/01-11/03	4	451	76	375	34	13.8
Pot Ridge C6	3/01-11/03	4	393	265	128	285	47.3
Pot Ridge C10	3/01-11/03	4	321	176	145	179	38.1
Oven Run D1	1/01-8/02	3	116	-38	154	103	19.0
Oven Run D2	1/01-8/02	3	-24	-48	24	103	3.1
Oven Run E1	3/00-11/03	5	205	70	135	468	25.9
Oven Run E2	3/00-11/03	5	70	11	59	611	14.8
Oven Run B2	3/01-7/03	22	308	141	167	905	28.0
Tangascootack 1	5/03-8/03	4	236	98	138	128	26.5
Glenwhite SqF		35	194	48	146	200	96.0
Oven Run B1	3/01-7/03	23	526	303	223	780	31.3
Pot Ridge A1	3/01-11/03	4	916	633	283	32	12.2
Pot Ridge A2	3/01-11/03	4	633	428	205	46	12.7
Coldstream A	6/03-10/03	3	350	22	328	209	41.1
Coldstream B	6/03-7/03	2	439	96	343	48	36.5

Fig. 3 compares the acidity removal in mg/L for the two periods. For seven of the systems, there is no decrease in acidity removal, and for three (Pot Ridge A1, Oven Run B1 and Tangascootack 1) the decrease is small (<20%) and may be within sampling error. At Coldstream A and B, the decrease is very large, about 60%, but the removal is still high, about 350 mg/L. The decreases appear significant at Oven Run B2 and Pot Ridge C6 and A2.

Fig. 4 compares the earlier and recent periods in terms of areal acidity removal rate (g/m^2/d). Again, six of the systems show negligible degradation. At one more (Oven Run B1) the decrease is less than 20%. The Coldstream sites show very large decreases in effectiveness, especially Coldstream B, and the other six sites show significant decreases. The possible reasons for this decrease in effectiveness are discussed below.

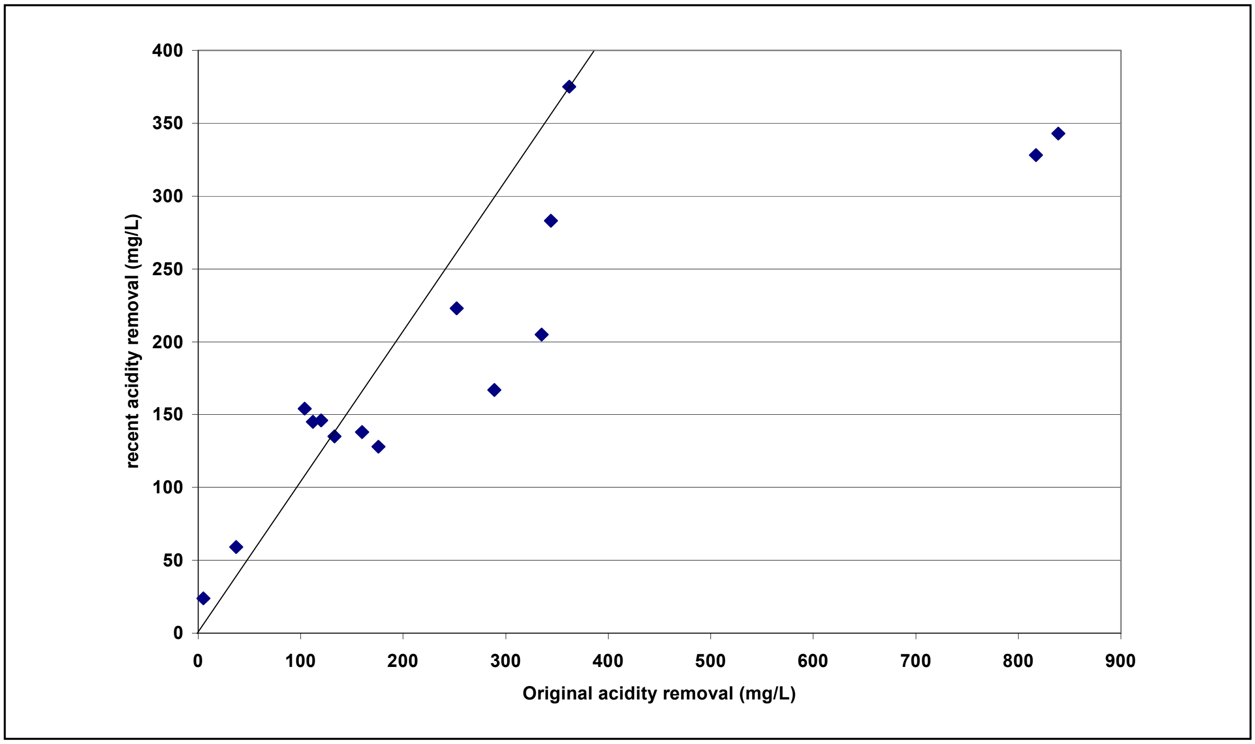

Figure 3. Change in acidity removal from original period to recent period. Line indicates the 1:1 relation expected for no change in removal.

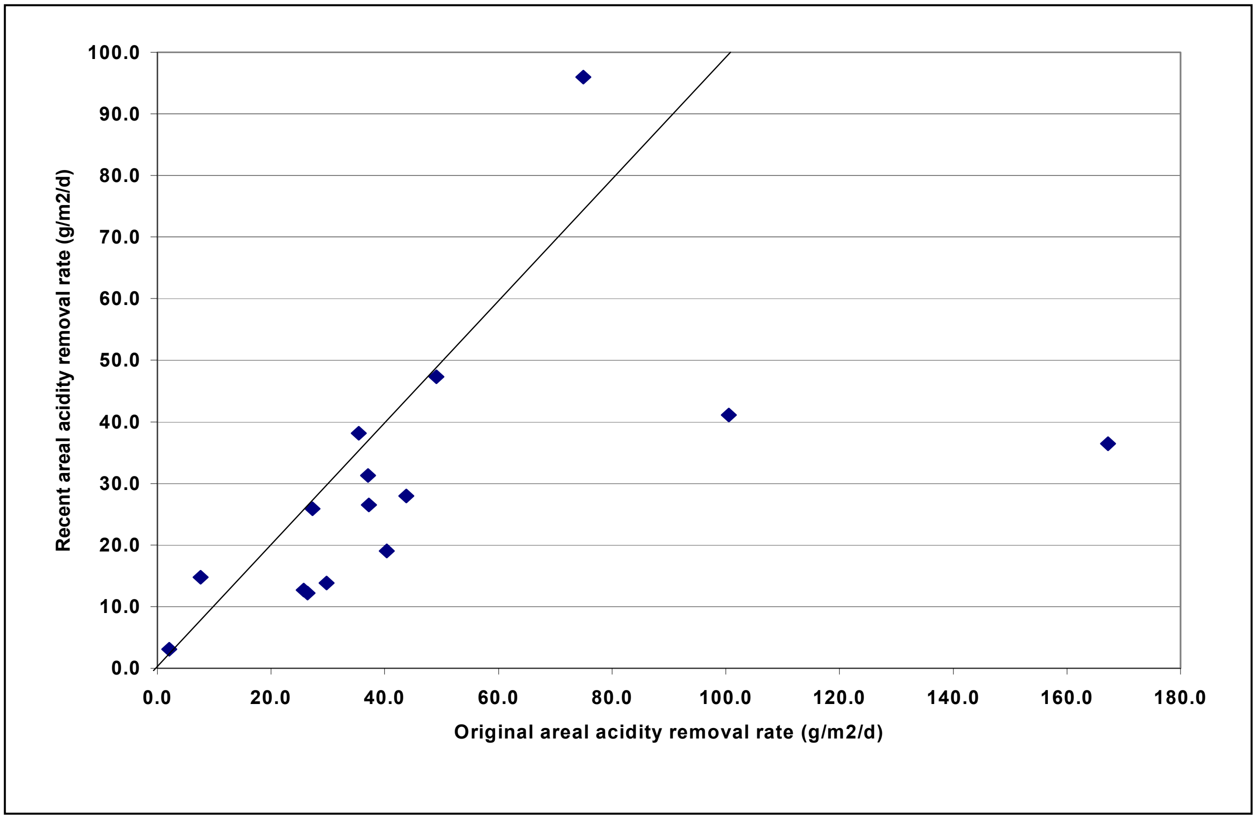

Figure 4. Change in areal acidity removal rate from original period to recent period. Line indicates the 1:1 relation expected for no change in removal rate.

Table 5. Evaluation of Problems at Vertical Flow Ponds (2003)

Name	Life to date	Flow	Acidity in	Acidity out	Al in	Problems?	Comment
	yrs	L/min	mg/L	mg/L	mg/L		
Howe Bridge W	12	144	323	106	0	Fe precipitation	Rebuilt at 11 yrs
Pot Ridge TEST	8	76	396	34	19	Fe pptn (partial)	Treats OK
Filson 1	7	116	241	175	14	Fe plugging	Inadequate size
Jennings	7	67	272	0	23	Pipe plugging	Corrected, OK
Sommerville	7	95	390	239	48	Channeling, Al pptn	No maint.
McKinley	7	57	101	4.1	2	OK	
Pot Ridge C6	6	215	399	223	16	Fe pptn(partial)	Partial treatment
Pot Ridge C10	6	215	201	89	12	OK	
Oven Run D1	6	323	127	50	2	OK	
Oven Run D2 H	6	335	38	23	1	OK	
Maust #1	6	177	154	0	3	OK	
Maust #2	6	177	0	0	0	OK	
Oven Run E1	5	500	217	84	15	OK	
Oven Run E2	5	500	72	35	8	OK	
Tangascootack 1	5	140	235	120	24	Cattail plugging	Inadequate size
Hortert	4	31	106	0	3	OK	
Harb-Walk(Ohiopy	4	42	205	4	0	Modified, OK?	
Cold Stream A	4	330	580	0	48	Al pptn?	Good treatment
Cold Stream B	4	70	500	0	35	Al pptn?	Good treatment
Glenwhite SqF	4	200	194	45	1	Fe plugging (no compost)	
Glasgow	4	40?	1000	670	149	Al plugging, rebuilt.	Decreased eff.
Oven Run B1	3	817	506	254	42	Al pptn, channeling?	Manifold added
Oven Run B2	3	817	242	0	28	OK	
Tangascootack 2	3?					OK	
Tangascootack 3	3?					OK	
Lambert	3	36	66	0	8	OK?	
Glenwhite SH	2	380	106	0	7	OK	

Problems Affecting Performance

A gradual decrease in performance is expected at VFS because of limestone consumption. However, some systems have required major maintenance, have visible problems or large decreases in performance, or have largely ceased to treat. Table 5 summarizes available data on such situations, arranged in order of system age.

Iron Hydroxide Accumulation on Compost

At the Howe Bridge system, the oldest VFS, the water level in recent years rose to the point that about half the water was escaping through the overflow, and in 2002 the system was rebuilt after 11 years of service. Influent averaged 193 mg/L Fe, 38 mg/L Mn and 323 mg/L acidity at a pH of 5.8 and a flow rate of 144 L/min. The major problem was decreased flow through the vertical flow unit due to accumulation of about 20 cm of red Fe-rich mud on top of the compost (Fig, 5). This large Fe accumulation arose because the influent was the high-Fe outflow of an

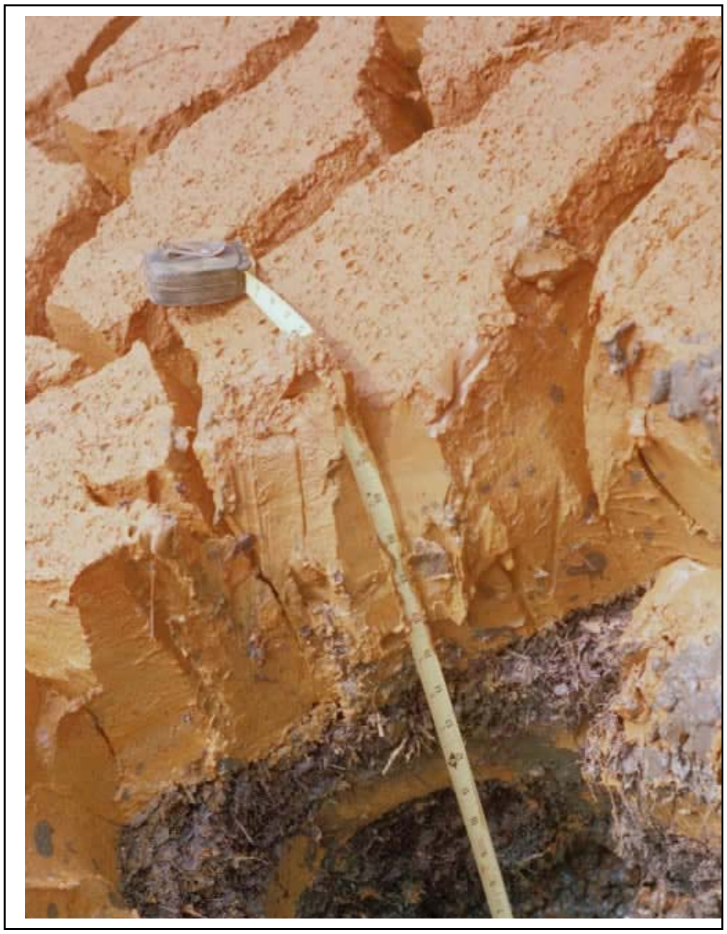

Figure 5. Photograph of Fe oxide precipitate layer on top of compost at Howe Bridge, June 2002. Scale in inches.

anoxic limestone drain. This high-Fe water flowed into a single water body containing a wetland area, an area of deeper water, and the vertical flow area, with no separations between. The Fe oxidized, precipitated and settled in all parts of the pond, including the vertical flow area. The system was rebuilt in 2002 with separate oxidation-settling and vertical flow units, and an additional vertical flow unit was added. The Fe precipitate is being processed for sale by Iron Oxide Recovery, Inc.

Accumulation of Fe precipitate on top of compost is typical of several other high-Fe systems, including Pot Ridge TEST, Pot Ridge A1 and A2, and probably others, such as Filson 1, Pot Ridge C6 and Glenwhite Squatter Falls. At Pot Ridge A1 and A2, flow has decreased to low values with major overflow, and C6 is treating only about half the flow. At the Pot Ridge sites, Fe accumulation has occurred in the VFS despite at least one oxidation-settling pond preceding the VFS. At C6, three ponds precede the VFS, yet Fe still precipitates in the VFS pond. At some of these systems, draining and removal of the Fe accumulation could probably largely restore them. At Glenwhite Squatter Falls, the system was built without compost, and was flushed to remove precipitate, but has reportedly accumulated significant amounts of Fe precipitate on the limestone (P.J. Shah, personal communication, 2003).

Pipe Plugging

Pipe plugging is known to have affected two systems. At Jennings, the flow decreased markedly, but after partially excavating the system, it was found that precipitation of Fe oxide in the outlet pipe was the cause (Margaret Dunn, personal communication). The Fe precipitation occurred where a small hole drilled to inhibit siphoning allowed ingress of air into the pipe. At Tangascootack, a major reason for near cessation of flow was growth of cattail roots into the submerged outlet pipe (Rose et al., this volume). Pipe plugging with Fe oxides was also a major problem on the buried inflow pipe at Pot Ridge C, where high-Fe water from a small pond was carried in a 15 cm pipe across Paint Creek and several hundred meters to the treatment area. Pipes involving oxidized water in the inflow and pond-to pond segments of systems should be avoided in constructing VFS with high Fe. Pipes should be used only in anoxic portions of systems.

Channeling of flow

Channeling or short circuiting of flow through the compost layer has been observed or inferred at several sites. Dye tests at Jennings suggest that most of the water flows down into the compost within a short distance, perhaps 5 m or less, from the inflow discharge (Peart and Cooper, 2000; Busler et al., 2002). However, the present author thinks that further study is needed on these experiments to verify that the effect is not explainable by slow advance of the enlarging dye front. At Somerville, Demchak et al. (2001) report effects on redox boundaries that suggest greater flow in some areas of the compost. At Oven Run B1, flushing normally has released large amounts of red water in addition to gray water with Al precipitate. It was observed that the compost had been washed away from the area near the inflow pipe, and a manifold was added to distribute the water over the system (Pam Milavec, personal

Table 5. Evaluation of problems at VFS

Name	Life to date yrs	Flow L/min	Acidity in mg/L	Acidity out mg/L	Al in mg/L	Problems?	Comment
Howe Bridge W	12	144	323	106	0	Fe precipitation	Rebuilt at 11 yrs
Pot Ridge TEST	8	76	396	34	19	Fe pptn (partial)	Treats OK
Filson 1	7	116	241	175	14	Fe plugging	Inadequate size
Jennings	7	67	272	0	23	Pipe plugging	Corrected, OK
Sommerville	7	95	390	239	48	Channeling, Al pptn	No maint.
McKinley	7	57	101	4.1	2	OK	
Pot Ridge C6	6	215	399	223	16	Fe pptn(partial)	Partial treatment
Pot Ridge C10	6	215	201	89	12	OK	
Oven Run D1	6	323	127	50	2	OK	
Oven Run D2 H	6	335	38	23	1	OK	
Maust #1	6	177	154	0	3	OK	
Maust #2	6	177	0	0	0	OK	
Oven Run E1	5	500	217	84	15	OK	
Oven Run E2	5	500	72	35	8	OK	
Tangascootack 1	5	140	235	120	24	Cattail plugging	Inadequate size
Hortert	4	31	106	0	3	OK	
Harb-Walk(Ohiopy	4	42	205	4	0	Modified, OK?	
Cold Stream A	4	330	580	0	48	Al pptn?	Good treatment
Cold Stream B	4	70	500	0	35	Al pptn?	Good treatment
Glenwhite SqF	4	200	194	45	1	Fe plugging (no compost)	
Glasgow	4	40?	1000	670	149	Al plugging, rebuilt.	Decreased eff.
Oven Run B1	3	817	506	254	42	Al pptn, channeling?	Manifold added
Oven Run B2	3	817	242	0	28	OK	
Tangascootack 2	3?					OK	
Tangascootack 3	3?					OK	
Lambert	3	36	66	0	8	OK?	
Glenwhite SH	2	380	106	0	7	OK	

communication). However, this change only partly solved the problem. A similar flushing of major amounts of red water was observed at a flushing system at the Pot Ridge A site. Possibly the compost is not thick enough to reduce all Fe at these sites.

Aluminum problems

Precipitation of Al on limestone was recognized early as a potential problem for VFS's, based partly on experience with Al plugging in an anoxic limestone drain at Jennings (Watzlaf et al., 1994). Flushing-type vertical flow systems (Aluminator, Kepler and McCleary 1997) were proposed and have been constructed in recent years on most systems with appreciable influent Al concentrations. The intent of these systems is to remove Al precipitate accumulated in the limestone bed of the VFS by periodic flushing with a rapid flow of water through the system.

A clear case of plugging of a VFS by Al precipitate is reported from the Glasgow (Cambria Mills) vertical flow system (Robert Hedin, personal communication). This system, which initially received about 150 mg/L Al and 280 mg/L Fe at a flow rate of more than 200 L/min, is reported to have stopped flowing in about 6 months, and when excavated, showed that about 0.2 m at the top of the limestone bed was largely filled with white precipitate. The system was rebuilt, the flow to the system was cut in half, and the system is flushable (though the flushing schedule is unknown). The system appears to be removing considerable acidity at present, after several years.

At other systems, the problem from Al appears to be decreased effectiveness with time, rather than plugging. It was shown above that some systems decreased in acidity removal and in areal acidity removal rate with time. Figure 6 plots decrease in acidity removal (mg/L) vs. the influent Al (mg/L). Sites with influent Al concentration <15 mg/L commonly increased in acidity removal in the later period (possibly due to limited sampling), but sites with an influent Al >20 mg/L have nearly all declined in effectiveness. Plots of areal acidity loading ($g/m^2/d$) and cumulative Al flux (g/m^2) showed the same trend but with no sharp cutoff. It seems clear that Al greater than about 20 mg/L can cause long-term problems by decreasing effectiveness, but complete plugging is recorded only for one site. The Coldstream sites and Oven Run B1 have been flushed regularly, but are declining in effectiveness, possibly from Al accumulation. Also, the data of Watzlaf et al. (2003) and Rose et al. (this volume) indicate that less than 5% of the accumulated Al is removed by flushing, so this design does not seem to solve the Al problem.

The decreased effectiveness is attributed to a decreased reaction rate of Al-coated limestone. The Al coating tends to be gelatinous, with an open structure, so it probably does not prevent reaction, but possibly diffusion of reaction products Ca and HCO$_3$ through the coating is expected to slow reaction. In addition, precipitation of crystalline gypsum beneath the coating has been reported (Hammarstrom et al., 2003; Rose et al., this volume). The gypsum may have a major effect on reaction rate because of its dense crystalline structure.

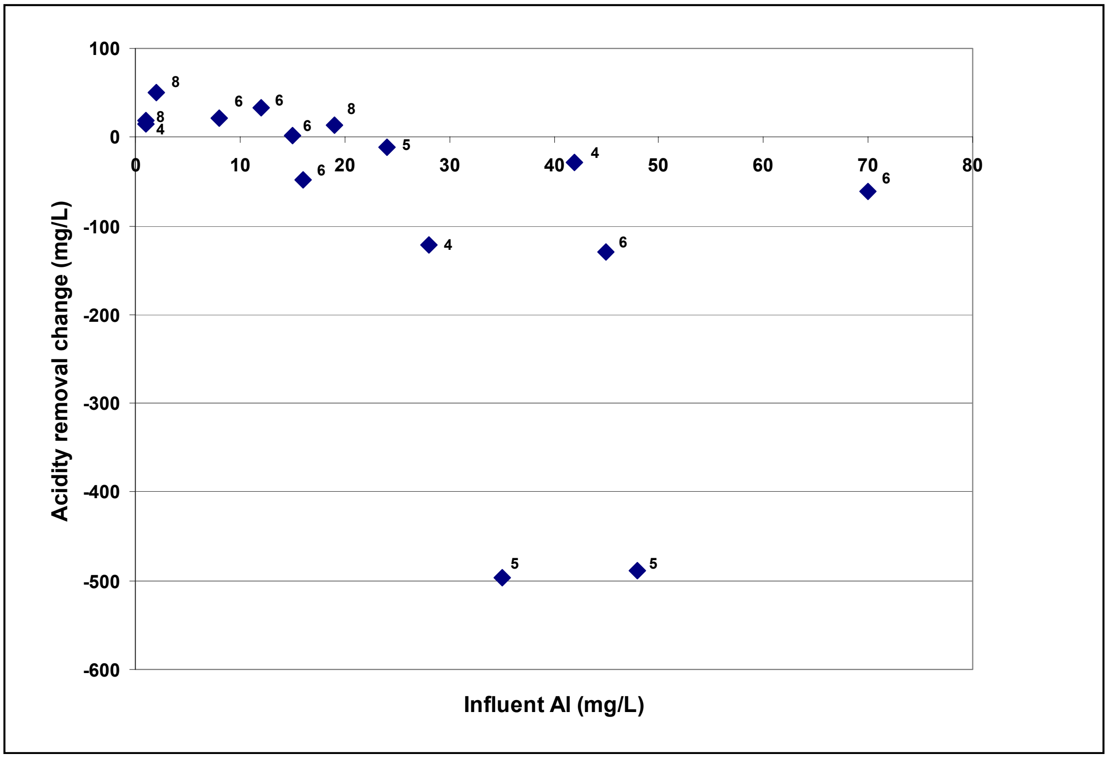

Figure 6. Change in acidity removal (mg/L) as a function of influent Al concentration. Change is from data prior to 2001 vs. more recent data (Table 4). Numbers next to points are the number of years the site has experienced inflow.

In view of the significant decrease in effectiveness caused by Al, construction of systems with limestone-amended compost may be a preferable alternative. In these systems, the fine limestone particles are completely replaced by Al and Fe precipitates, rather than being coated.

Conclusions

The revised understanding of acidity leads to a slight decrease in the effectiveness of vertical flow ponds in terms of areal acidity removal rate, to a rate of about 34 g/m^2/d compared to 40 g/m^2/d previously indicated.

Addition of fine limestone to compost clearly increases the removal rate, and is a promising method for handling high-Al discharges.

Problems encountered at a few VFP's include Fe precipitation on top of compost, pipe plugging from several causes, channeling and decreased effectiveness due to Al coating of limestone. Systems with influent Al exceeding about 20 mg/L have experienced decreases in acidity removal. Complete plugging by Al precipitates appears to occur only at very high influent Al, but coating of limestone with Al precipitate tends to decrease reaction rate, and may be accentuated by precipitation of gypsum on the limestone beneath the Al coating.

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